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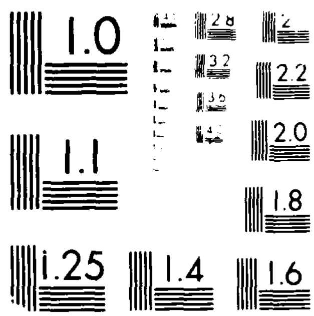
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HIGH-EFFICIENCY THIN-FILM SILICON-ON-GaP SOLAR CELL FOR IMPROVED RADIATION RESISTANCE

J.S. Culik
Astrosystems, Inc./Astropower Division
30 Lovett Avenue
Newark, Delaware 19711

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6563

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MICHAEL A. CHUNG, 2Lt, USAF
Electrical Engineer
Photovoltaics
Power Components Branch

PAUL R. BERTHEAUD, Chief
Power Components Branch
Aerospace Power Division

FOR THE COMMANDER:

JAMES D. REAMS
Aerospace Power Division
Aero Propulsion Laboratory

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The ultimate high-efficiency silicon solar cell is a light-trapping, thin-film silicon structure epitaxially-grown on an oxide-overcoated substrate such as silicon or gallium phosphide (GaP). In addition to high performance, this thin-base silicon device is more tolerant of radiation effects than a thick-base solar cell because this structure is less sensitive to reductions in minority-carrier diffusion length. The oxide overcoating layer, an integral part of this design, will serve as a dielectric back surface reflector leading to light trapping, and it will also eliminate dangling bonds in the overgrown silicon layer, effectively passivating the silicon-oxide interface and reducing back surface recombination. A heterojunction contact formed at the silicon-GaP interface through vias

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in the oxide will minimize back ohmic contact losses. And finally, the wide bandgap, infrared-transparent GaP substrate will allow long wavelength photons to pass through the structure, which will reduce the operating temperature. Front surface shadowing and recombination can be reduced by the further application of GaP as a transparent, low-recombination, heterojunction contact to the solar cell emitter. Since the active device is silicon, device processing can take advantage of standard, space-qualified, silicon solar cell fabrication procedures.

During the course of this Phase I effort, we have demonstrated: (1) laterally-overgrown, continuous silicon films grown through vias on oxide-overcoated silicon substrates using selective epitaxy; (2) significant current enhancement in thin-base solar cells due to light trapping; (3) thin-film silicon-on-oxide solar cells with AMO energy conversion efficiencies of 11.2%; (4) heteroepitaxial growth of silicon through vias in oxide-overcoated GaP substrates; and (5) heteroepitaxial growth of GaP on silicon substrates. All of these films were grown by liquid phase epitaxy, a semiconductor growth technique capable of rapidly producing large area, photovoltaic films using simple and inexpensive equipment.

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1. INTRODUCTION

The ultimate high-efficiency crystalline silicon solar cell design consists of a thin film of electrically-active silicon grown in a light-trapping configuration on an infrared-transparent, wide-bandgap, hetero-contact substrate, such as gallium phosphide (GaP). An oxide layer between the substrate and the active layer will eliminate dangling bonds in the overgrown silicon layer, effectively passivating the silicon-oxide interface and reducing back surface recombination, and it will also serve as a dielectric back surface reflector leading to light trapping. A heterojunction contact formed at the silicon-GaP interface through vias in the oxide will minimize back ohmic contact losses. And finally, the wide-bandgap, infrared-transparent GaP substrate will allow long wavelength photons to pass through the structure, which will reduce the operating temperature. Front surface shadowing and recombination can be reduced by the further application of GaP as a transparent, low-recombination, heterojunction contact to the solar cell emitter. Since the active device is silicon, device processing can take advantage of standard, space-qualified, silicon solar cell fabrication procedures.

Mauk and Barnett [1,2] have recently reported on thin-film silicon-on-oxide solar cells that show the effect of optical confinement (or "light-trapping") on long-wavelength photocurrent. This work is an extension of their effort to develop a high-performance, light-trapping, crystalline thin-film silicon solar cell.

Silicon solar cell designs that incorporate optical confinement, or light-trapping, will lead to increased radiation resistance and very high performance. The primary performance improvement due to light-trapping is enhanced photocurrent because absorbed photons with energy greater than the bandgap will generate carriers well within a minority-carrier diffusion length of the collecting junction. Therefore, a thin film of even an indirect bandgap material like silicon can be made to have photon absorption properties that are equivalent to that of a thick layer. Enhanced photocurrent leads to significantly increased open-circuit voltage and fill-factor, and therefore improved overall conversion efficiency; efficiencies approaching the practical limits of 21.5% (AM0) are achievable using light-trapping designs with silicon. With a light-trapping thin-film design, photocurrent is not very sensitive to minority-carrier lifetime; therefore, not only will this device be of high efficiency, it will also be less sensitive than present thick-base designs to radiation damage.

Technology to fabricate unsupported (50-micron overall thickness) silicon solar cells with AM0 conversion efficiencies of 14 to 15% has existed for about 10 years [3,4]. However, processing and handling these particular devices is difficult, and as the device area increases, so too does the processing difficulty. As a result, conventional "thin" silicon cells are typically more than 150 microns thick and do not operate as "thin-base" devices. The goal of our work is the fabrication of a high-efficiency, thin-film, single-crystal silicon solar cell on a thicker, non-electrically-active, supporting substrate.

2. REVIEW OF HIGH EFFICIENCY SOLAR CELL DESIGNS

There are several designs that are presently being utilized to achieve high conversion efficiency in silicon solar cells. A brief description of each design follows.

"Conventional" high-efficiency silicon solar cells are patterned after the "violet" cell pioneered by Lindmayer and Allison in 1973 [5]. This design is characterized by a thick (typically 300 microns), p-type base with resistivity in the 1 to 10 ohm-cm range, a heavily-doped thin emitter to maximize short-wavelength photogeneration and collection, fine-line metallization to reduce shadowing, and a back surface field region ("BSF") and/or a back surface reflector ("BSR") to enhance long-wavelength response. Conversion efficiency as high as 16% (AM0) is achievable with this design.

A major increase in conversion efficiency resulted from use of high majority-carrier concentration, long minority-carrier lifetime silicon (Wacker *float-zone*, 0.1 *ohm-cm*, 300 to 400 micron thick) and the incorporation of surface passivation and reduced-area contacts. This design strategy, which has the primary goal of boosting open-circuit voltage, is best shown in the work of Green, et. al. [6]. We calculate, from their results, that AM0 efficiencies of 19.7% are achievable. It is important to note, however, that this design depends on very high base dopant concentration (greater than 10^{17}/cc) and very long minority-carrier diffusion length (longer than 200 microns) for its high performance.

Another recent high-performance design has been developed by the group at Stanford [7]. This design is characterized by a texture-etched front surface, co-planar back-surface point contacts, oxide-passivated surfaces, and a thin base layer (in the range of 100 to 200 microns) of high-resistivity (about 400 ohm-cm), very long minority-carrier lifetime (float zone) silicon. Both the thinness of the base and front-surface texturing are used for light-trapping in order to increase photon absorption and carrier generation. With this design, we calculate that AM0 efficiencies of 19.9% can be achieved. However, this design is also sensitive to the thickness of the base layer and to minority-carrier lifetime. To improve the efficiency, the solar cell must be thinner (less than 100 microns) and/or have even longer minority-carrier lifetime.

In summary, present realizations of high efficiency silicon solar cells based on "thick" base designs are inherently limited by the need for very high minority-carrier diffusion length and are therefore not tolerant of lifetime degradation that may result from radiation damage. The lifetime requirement is particularly difficult to achieve as the base majority-carrier concentration increases due to heavy doping lifetime degradation effects. The coplanar back contact design attempts to remove this obstacle by utilizing high resistivity material; however, high minority- carrier lifetime is still a requirement of this device. In contrast, our thin-film design allows the use of low-lifetime, low-resistivity material and is, therefore, more radiation tolerant than any of these thick-base designs.

3. LIGHT-TRAPPING AND HETEROJUNCTION CONTACT SOLAR CELL DESIGN CONCEPTS

Future improvements in silicon solar cell performance will result from increases in open-circuit voltage, rather than short-circuit current. Electronically, the open-circuit voltage of a solar cell is influenced by three parameters: operating temperature, photo-current, and recombination current. Of these, minority-carrier recombination is the most critical because it can change by orders of magnitude for different solar cell designs, materials, and fabrication processes. Minority carriers may recombine in each of the various regions of the solar cell -- in the base, within the junction depletion region, in the emitter, at any surface, and at the front and back contacts.

A recently-developed solar cell design concept that enhances photocurrent and minimizes base recombination is based on photon- or light-trapping [8], shown schematically in Figure 3.1. The generalized conditions for light-trapping are: (1) base thickness significantly less than the absorption depth for all photons whose energy is greater than the bandgap; (2) both surfaces internally reflective; and (3) at least one textured surface. Theoretically, the effective optical path length can be increased by up to a factor of $4n^2$ [9], where n is the index of refraction; for silicon, the index of refraction is about 3.5, and the effective optical path length can be increased by a factor of about 50. Therefore, a thin film of even an indirect bandgap material like silicon can be made to have photon absorption properties that are equivalent to that of a thick layer. With respect to optical absorption, a 20-micron thick layer of silicon can ideally appear to be 1-mm thick. However, since the film is only 20 microns thick, photogenerated carriers need travel at most only 20 microns, and therefore the photogenerated current will be greater than that which would be collected from a thicker layer without light-trapping.

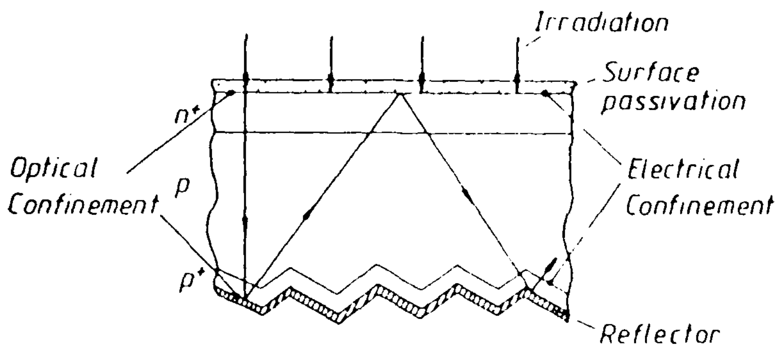

Figure 3.1 Light-trapping solar cell structure (from Goetzberger, et.al. [8]).

In addition to enhanced photocurrent due to light-trapping, a thin-base solar cell will also have improved open-circuit voltage due to the smaller recombination volume of the base [10]. Green [11] has theoretically shown that further increases in open-circuit voltage can be achieved if the solar cell is operated under high-injection conditions.

A practical consequence of the light-trapping, thin-base design is that the back surface, located well within a minority-carrier diffusion length of the junction, is now capable of competing more successfully with the junction for minority carriers. On the emitter side of the collecting junction, minority-carrier losses are principally related to recombination at the front surface. Therefore, low recombination at both the front and back surfaces is critically necessary in order to realize any benefit from a light-trapping design.

One of the many good characteristics of silicon is its ability to form a thermal oxide with excellent surface passivating qualities; surface recombination velocities below 10 cm/sec have recently been reported [12]. Therefore, recombination at surfaces other than contacts can be controlled by passivating the silicon surface with its native thermal oxide (SiO_2). However, an ohmic contact has, by definition, a near-infinite recombination velocity; as a result, recombination at the ohmic contacts will become the dominant loss mechanism of any surface-passivated, high-efficiency silicon solar cell design.

Besides simply minimizing the actual ohmic contact area, there are several design solutions to this problem of high-recombination contacts. One possibility is a tunneling contact [13], which may result when a thin SiO_2 layer (on the order of 20 Angstroms or less) is deposited beneath the metal contact. If the work function of the metal does not cause depletion of majority carriers under the oxide, then current conduction may occur by a majority-carrier tunnelling mechanism without minority-carrier annihilation. However, the conditions on the thickness and integrity of the oxide layer and on the work function of the metal severely restrict the usefulness and reliability of the tunnelling contact.

Contact recombination may also be reduced by using a high-low junction structure. A high-low junction results when the surface layer is doped much more heavily than the bulk region. An electric field is then created that inhibits minority-carrier flow to the surface, in effect creating a minority-carrier "mirror" that "reflects" carriers away from the surface and back toward the collecting junction. For an effective high-low junction, the dopant concentration difference between the low- and high-resistivity regions must be at least three orders of magnitude [14]. However, for minimum recombination, a bulk region should be doped as heavily as possible, within the constraints of Auger recombination and lifetime reduction. Therefore, use of a high-low junction involves a trade-off between contact and bulk recombination; neither can be optimized independently of the other.

An alternative to high-low junction and tunnelling contacts as recombination-reducing structures is a heterojunction. The heterojunction contact structure consists of a wide-bandgap surface layer joined to a smaller-bandgap (in this case, silicon) bulk region [15]. If the wide-bandgap layer is doped the same type as the narrow-bandgap material, then it is possible to create a minority-carrier "mirror" at the junction in the direction of the narrow-bandgap material by appropriately bending the conduction band (for n-type) or valence band (for p-type).

The principal advantage of the heterojunction over the high-low junction is that the potential barrier is determined primarily by the difference in energy bandgaps, not majority-carrier concentration. This means that the energy barrier will not only be much larger, but that it will also be fairly insensitive to the resistivity of the narrow-bandgap absorber region. The second advantage is that the heterojunction structure allows an ohmic, rather than a tunnelling, contact to be made to the device. Current may easily flow across the junction without minority-carrier recombination or majority-carrier tunnelling. Therefore, heterojunction contacts will not suffer the series resistance losses that tend to occur with tunnelling contacts. One further advantage of a heterojunction has to do with the optical properties of a heterojunction structure. The wide-bandgap layer of a heterojunction is transparent to photons that are absorbed by the narrow-bandgap layer. When applied to the solar cell top surface, the heterojunction contact will allow useful photons to reach the absorber layer; and only very energetic, short-wavelength photons will be absorbed by the wide-bandgap layer. Because of the many good qualities of heterojunctions, successful application of the appropriate heterojunction contact will result in significant improvements in silicon solar cell performance, especially for a light-trapping thin-film design.

The effectiveness of the GaP-Si heterojunction as a low recombination contact is critically dependent on its ability to keep minority carriers from getting through the GaP layer to the surface, which is dependent on the electronic band structure at the interface. The band diagrams of a p-GaP on p-Si heterojunction and an n-GaP on n-Si heterojunction are shown in Figures 3.2a and 3.2b, respectively. With the GaP/Si system, two types of junctions occur: a blocking junction, as in the case of the n/n heterojunction, and a band-bending junction, as in the case of the p/p heterostructure. A band structure with band bending is preferable, though not necessary, for low junction recombination. If the heterostructure functions mainly as a blocking junction, then the quality of the metallurgical interface becomes important; any growth-related interface states (say, due to impurities or stress-induced dislocations) will become major recombination sites and will detract significantly from the minority-carrier "mirror" properties of the heterostructure. For the heterjunction with significant band bending, the electric field at the interface will be quite large and will tend to minimize the effect of interface states. Of the two GaP heterostructures with silicon, the band structure of the p-on-p is more ideal.

Fig. 2(a) Fig. 2(b)

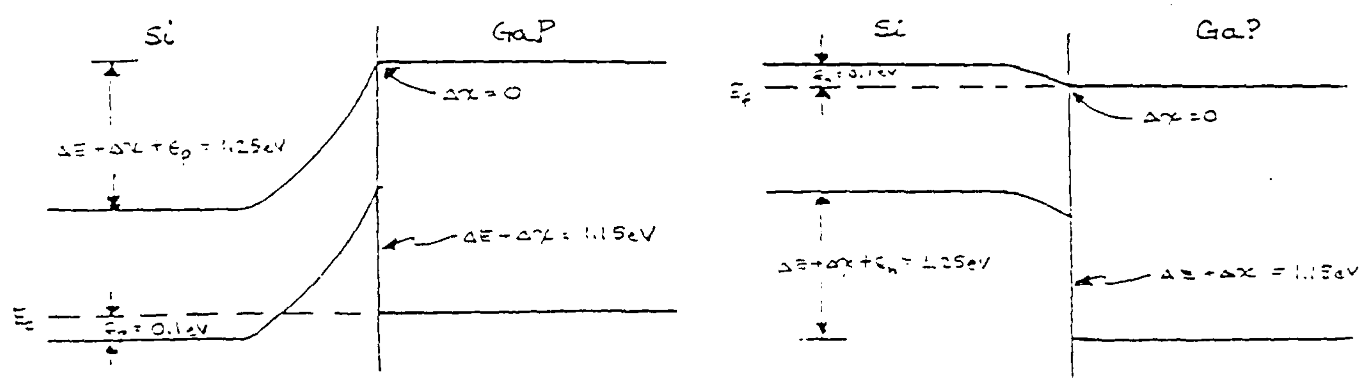

Figure 3.2 Silicon-gallium phosphide band diagram: (a) p-GaP, p-Si; (b) n-GaP, n-Si.

4. THIN-FILM SILICON SOLAR CELL DESIGN

Due to processing and handling difficulties, practical "thin" silicon cells are typically thicker than 150 microns. The goal of this work is the fabrication of a robust, high-efficiency, single-crystal silicon solar cell, whose base thickness is significantly less than 50 microns thick. To accomplish this, the thin-film device will be epitaxially grown onto a thick, non-electrically-active, supporting substrate. The choice of substrate material is important because the active silicon layer must be grown onto the substrate, and the presence of the substrate must not degrade and, preferably, will enhance the performance of the silicon device.

During the course of this work we have grown thin-film silicon layers on substrates of silicon and gallium phosphide (GaP) by using the technique of liquid phase epitaxy. We chose GaP as a candidate substrate because it is very important that the substrate be lattice-matched to the silicon so that grown-in stresses, and the resulting dislocations, will be minimized. Minimizing the stress is essential for growing layers with high minority-carrier lifetime. At growth temperatures of 700 to 900°C, the lattice mismatch between silicon and GaP is less than 0.4%. Because the lattice constant of GaP is slightly larger than that of silicon, the silicon layer will be under slight tension. The thermal expansion coefficient of silicon is less than that of GaP, so that the grown-in stress at the crystal interface due to lattice mismatch will decrease as the crystal cools. Additionally, if the silicon epitaxial layer is grown through vias on a GaP substrate over-coated with a masking layer of SiO_2, then the area of the lattice-mismatched silicon will be limited to the heteroepitaxial layer grown through the vias, the lattice-mismatch stress is minimized, and the possibility of creating grown-in interfacial dislocations will be significantly reduced. Silicon-GaP lattice-mismatch dislocations will not propagate laterally over the majority of the surface that is oxide overcoated because, since the epitaxial layer is grown under equilibrium conditions, the silicon film will grow such that all bonds are satisfied, and the epitaxial layer surface will be passivated by the oxide.

The choice of liquid phase epitaxy (LPE) as a growth technique is based on its demonstrated ability to produce material with excellent electronic characteristics. The high performance of devices fabricated using liquid phase epitaxy can be attributed to the exact stoichiometry control and the tendency of impurities to segregate to the liquid rather than the solid, which results in fewer deep levels and longer minority-carrier lifetimes. In addition to these benefits, LPE has the advantage of yielding layers of accurately-controlled composition and thickness. Also, the simplicity and low cost of LPE equipment leads to lower fabrication and scale-up costs for an actual production line. Liquid phase epitaxy is used routinely to grow high-quality layers of semiconductor and garnet material, material that is used in light-emitting diodes and lasers, magnetic bubble memories, and GaAs solar cells.

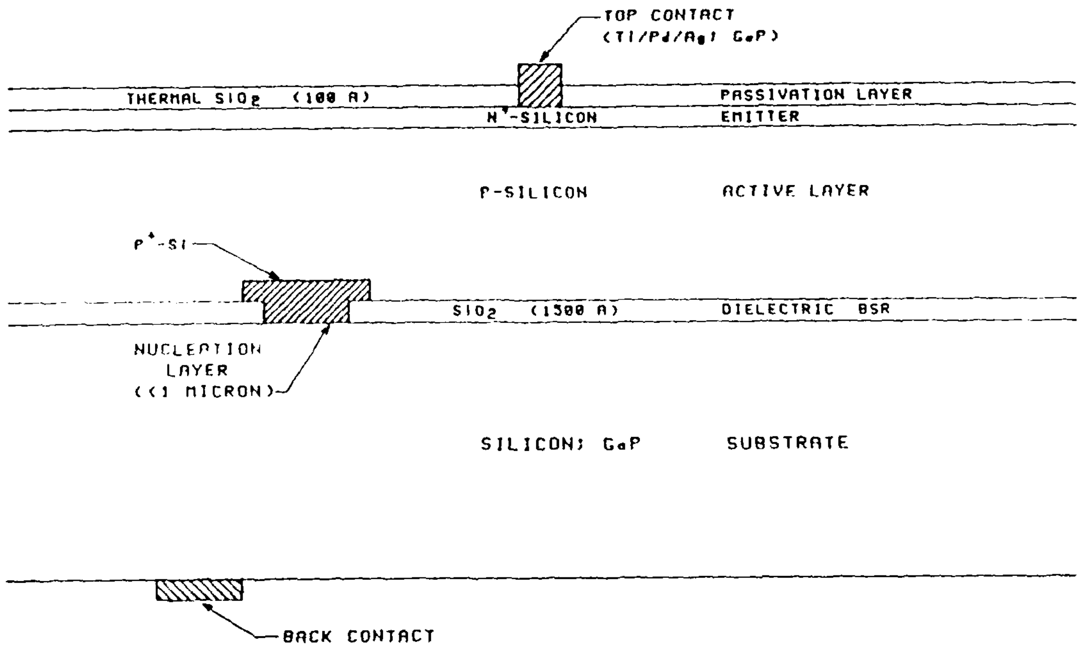

Figure 4.1 Structure of the light-trapping thin-film silicon solar cell.

A schematic diagram of our thin-film silicon-on-oxide solar cells is shown in Figure 4.1. There are several distinct performance features of this thin-film silicon solar cell. First, since the active silicon layer will be very thin, the short-circuit current and open-circuit voltage of the solar cell will be virtually insensitive to variations in minority-carrier lifetime and to degradation of minority-carrier lifetime due to radiation damage. In contrast, other thick-base, high efficiency silicon solar cell designs require float-zone silicon with lifetimes of 100 to 500 microseconds. As a result, these thick-base designs are very sensitive to radiation damage that reduces the minority-carrier lifetime.

Second, thin-film silicon solar cells typically suffer from low short-circuit current due to reduced light absorption in the narrow base region. With our design, the oxide layer between the silicon and the substrate is used as a dielectric back surface reflector, which will recapture these photons by light trapping, enhance the light-generated current, and increase the short-circuit current to at least that of a thick-base solar cell.

Third, the combination of wide-bandgap GaP substrate with silicon may result in the formation of a heterojunction contact at the interface which will reduce the minority-carrier recombination losses typically associated with an ohmic contact. For a thin-base device, this feature will result in a substantial improvement in open-circuit voltage and conversion efficiency.

In addition, a GaP substrate is transparent to photons whose energy is less than the bandgap of silicon, and absorption of this infrared radiation by the solar cell will be substantially reduced. Therefore, a thin-film silicon-on-GaP device will operate at a significantly lower temperature; this feature alone will result in an improvement in open-circuit voltage of approximately 2 mV per degree Centigrade that the junction temperature is reduced.

Finally, processing of the thin-film silicon can take advantage of standard silicon solar cell fabrication procedures, such as diffused emitters, Ti-Pd-silver front metallization, and multiple layer anti-reflection coatings, that are qualified for space use. The only new technology that must be space-qualified is the rear contact to the GaP substrate. However, even in this area technology for making highly reliable contacts to GaP exists and is used for routinely making contacts to commercial light-emitting diodes. In addition, silicon processes that promise even higher efficiencies in thick-base silicon solar cells, such as oxide-passivated surfaces, improved emitter junctions, heterojunction emitter contacts, and improved anti-reflection coatings, are all applicable to this design and can be added in sequence, just as in conventional thick-base silicon solar cell designs.

In summary, whereas previous high-efficiency silicon solar cell designs increased the devices' sensitivity to radiation damage, infrared radiation, or breakage, our design combines high conversion efficiency, radiation resistance, low operating temperature, and ease of manufacture and handling. This novel design is potentially the highest-efficiency, radiation-tolerant silicon solar cell design that can be demonstrated using practical technology.

5. SELECTIVE EPITAXY FILM GROWTH DEVELOPMENT

Liquid phase epitaxy is a material growth technique in which an epitaxial layer is grown on a single-crystal substrate by deposition from a saturated metal solution. The material growth process is based on phase equilibria of various solvent systems, nucleation and growth kinetics, and mechanisms that affect crystal morphology and the formation of crystalline defects. Liquid phase epitaxy layers were grown in this Phase I program using a multiple-bin liquid phase epitaxial slider boat growth system similar to that used by Nelson [16] A drawing of this apparatus is shown in Figure 5.1.

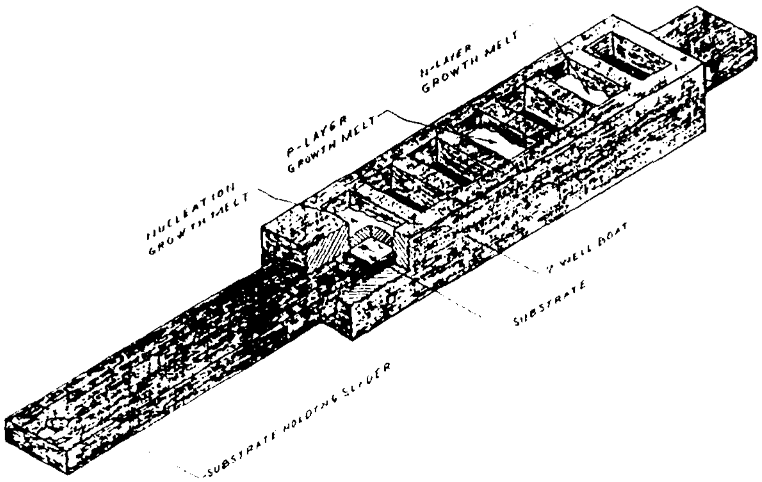

Figure 5.1. Liquid phase epitaxy slider boat growth apparatus.

The slider boat growth apparatus serves as a substrate holder and melt container for the metallic growth solutions. The slider boat system functions by physically positioning the substrate wafer in and out of any particular growth solution. The graphite slider/melt holder apparatus fits into a controlled-atmosphere furnace that can be temperature-programmed and temperature-ramped. Heating causes solid to enter the solution; cooling causes material in the solution to deposit onto the substrate. The melts are "charged" with separate source wafers of silicon, and the silicon doping concentration can be modified by adding dopants to the melts. Layers are grown on the substrate by imposing a temperature ramp; as the temperature falls in a particular melt, a layer of material that is dissolved in the metallic solvent will epitaxially grow onto the substrate.

Advantages of the slider apparatus over other techniques, such as dipping, are: (1) the substrate wafer can be easily brought in and out of contact with the melts; (2) several melts can be used in sequence; (3) growth is restricted to a single side of the wafer; (4) substrate-solution contact is from the bottom of the melt where there are no floating oxides or other contaminants; (5) excess solution can be wiped off the wafer by the slider action of the boat; and (6) thermal equilibration and temperature profiling are greatly improved. The graphite growth apparatus is contained in a fused silica tube which is purged with flowing hydrogen or mixtures of hydrogen and nitrogen. Both tube and slider system fit into a four-zone, microprocessor-controlled furnace which is used to program the temperature gradients. The substrate, held in the slider, is moved through the various melts by a pushrod mechanism. Once the metallic solvent system is specified, the experimental growth parameters are substrate orientation and preparation, solution composition (including dopants), initial growth temperature, cooling rate, and growth time.

Selective epitaxial growth differs from conventional epitaxy in that the substrate is masked by an oxide layer, and growth is initiated (through "wetting" and "nucleation") only at holes ("vias") that are opened in the masking oxide layer. Use of this technique allows device-quality layers to be grown on lattice-mismatched substrates. We have used this technique to grow films of GaP-on-GaAs and GaAsP-on-GaP. The advantages of the selective epitaxy technique are that stresses caused by lattice mismatch and differential thermal expansion are effectively limited to the via area, which is only a small fraction of the total surface area. In addition, the oxide layer is used to "passivate" the back (or bottom) surface of the film and also acts as an optical mirror, due to the index of refraction difference between the grown film and the oxide layer.

The approach used to realize this substrate was to first develop a silicon nucleation layer for use with GaP substrates; the necessity of this layer was due to the propensity of the Sn-based solvent used to grow the active silicon layer to solubilize the GaP substrate. However, once the nucleation layer is complete and the vias are filled with silicon, the GaP substrate would appear to be equivalent to an oxide-overcoated silicon substrate. A selective epitaxy growth procedure that works on GaP will necessarily work on silicon. Therefore, with this approach, only one nucleation and one film growth process would need to be developed, and a silicon substrate can be readily substituted for a GaP substrate, and vice versa.

Experiments to develop a thin-film, light-trapping heterojunction contact solar cell were divided into three areas: (1) silicon grown on oxide-overcoated silicon substrates, (2) silicon grown on oxide-overcoated GaP substrates, and (3) GaP grown on silicon substrates.

Thin, continuous films of silicon on oxide-overcoated silicon wafers were developed to demonstrate selective epitaxy with complete lateral overgrowth across the oxide layer. The substrates were typically used in "as-received" condition; they were not polished or otherwise prepared. The oxide layer was grown at 1000 C using dry O_2; the thickness of the SiO_2 layer was approximately 1500 Angstroms. Vias were patterned into the oxide with standard photolithographic techniques. Using a Sn-based solvent with the process and apparatus described above, silicon films were grown on the substrates, with the principal variables being the melt composition, temperature, cooling rate, and growth time. Figure 5.2 shows the surface of an edge section of a single-crystal film grown on an oxide-coated silicon substrate with 20-micron-wide linear via on 100-micron centers. The photograph was taken near the edge of the film, so that a portion of the original substrate (with oxide vias) is also visible. The film nucleates preferentially from the substrate (shown to the left in the picture), then grows up and laterally across the oxide layer, eventually joining and forming a continuous layer (shown to the right in the picture). There was no evidence of a grain boundary at the interface where the laterally grown layers meet. Best results were obtained when the vias were oriented along a <110> axis in the (111) plane. In addition to demonstrating the ability of selective epitaxy to produce continuous thin films of silicon on oxide layers, these results demonstrate a novel method to obtain reduced-area back contacts and oxide-passivated back surfaces for a light-trapping thin-film solar cell structure.

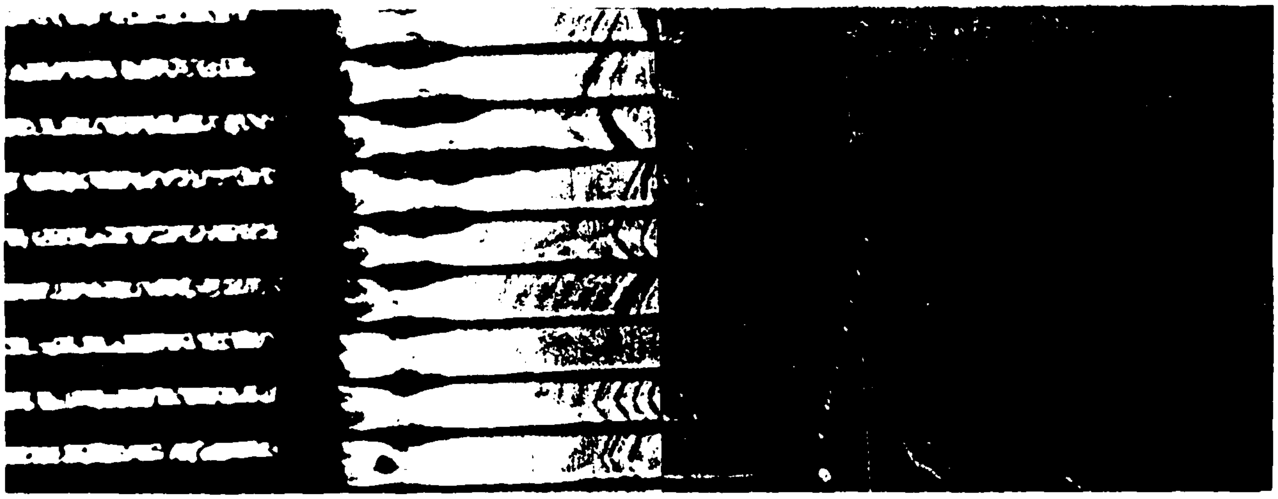

Figure 5.2 Crystalline silicon film grown by selective epitaxy on an oxide-overcoated silicon substrate. Vias (shown at the left) are 20 microns wide on 100-micron centers. (top view, 100X)

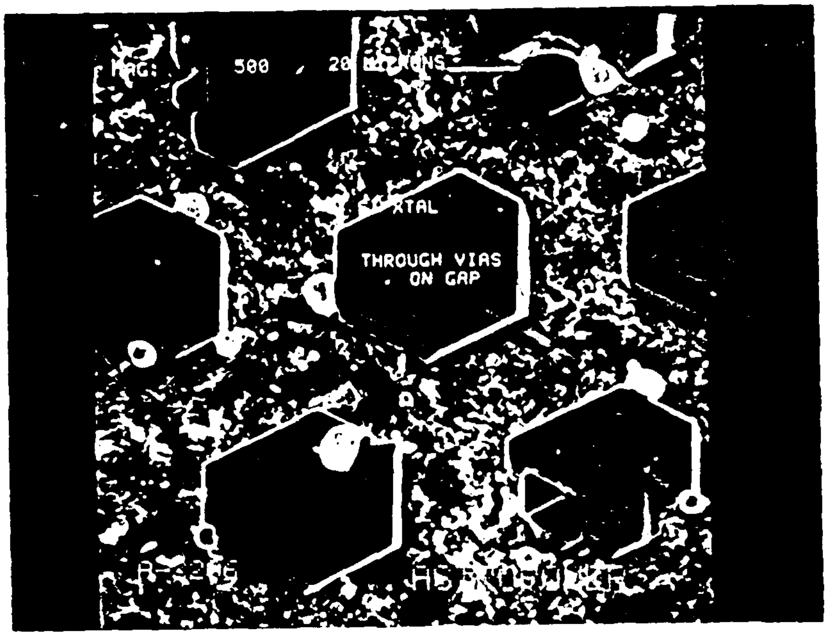

Figure 5.3 Silicon nucleation layer grown on an oxide-coated (111)-oriented GaP substrate, 25-micron-wide circular vias.

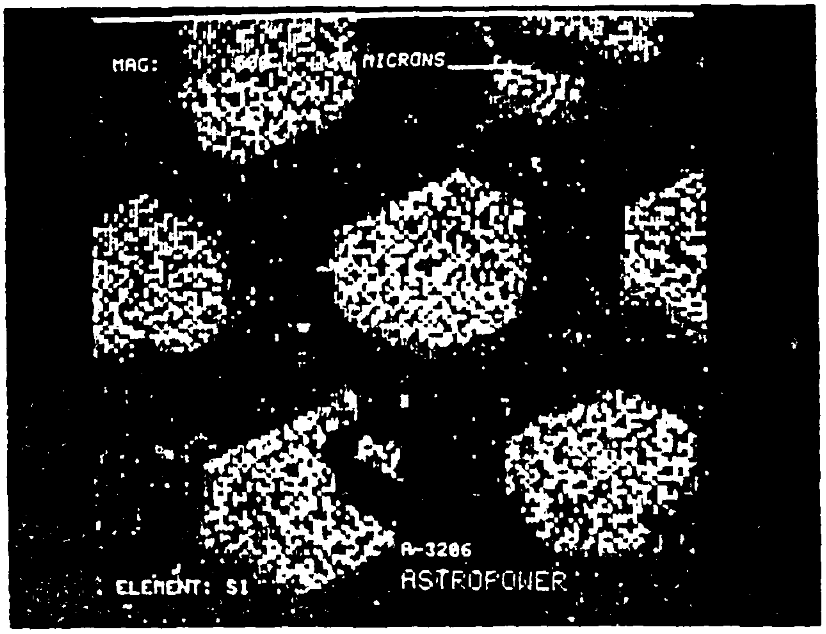

Figure 5.4 Energy dispersive x-ray (EDAX) scan of the film shown above, tuned for silicon.

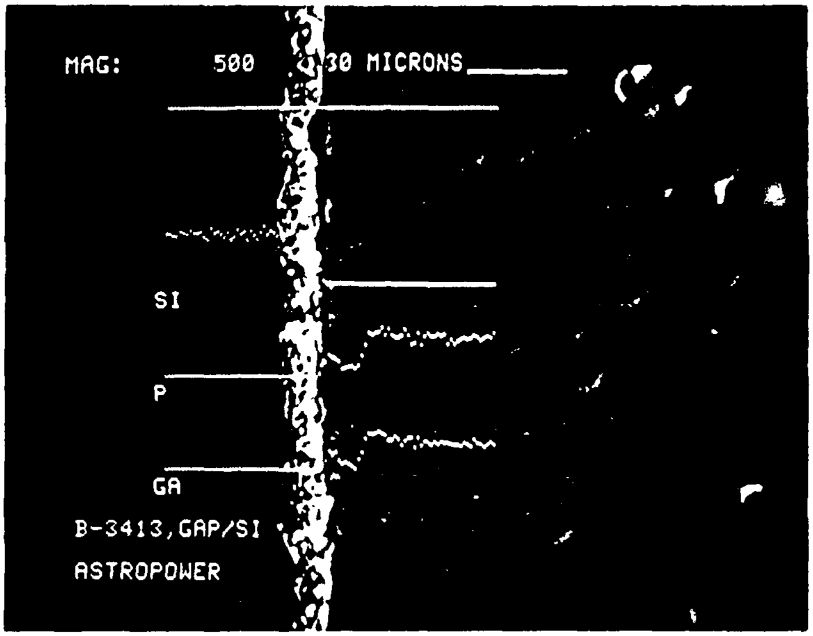

Figure 5.5 EDAX linescan across the top surface of GaP film grown on a (111)-oriented silicon substrate. Substrate surface is to the left, grown film is to the right

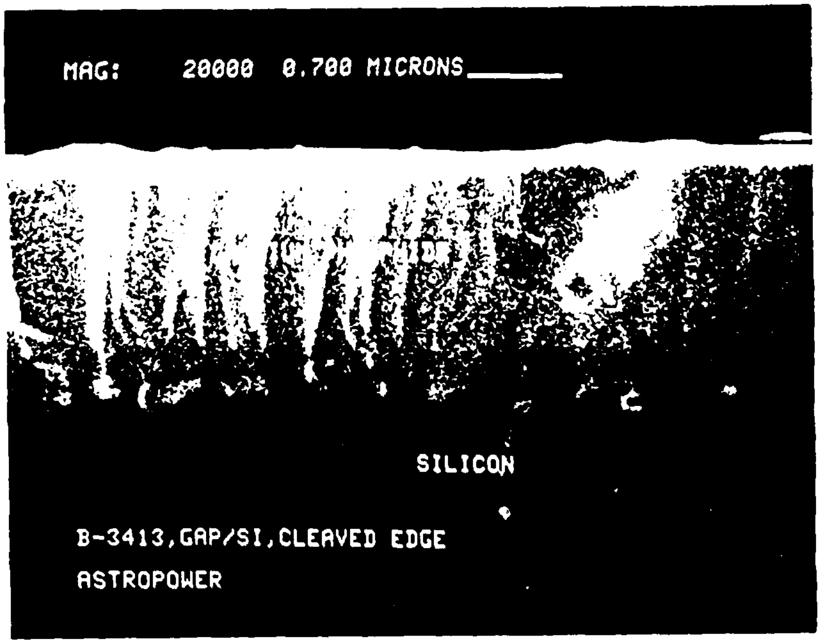

Figure 5.6 Cleaved edge of a GaP film grown on a silicon substrate.

The silicon-on-silicon selective epitaxy film growth process was applied to GaP substrates in order to develop a thin-film silicon cell structure with low-recombination, heterojunction back contacts. A thin nucleation layer was grown from a Ga-Bi solution. Figure 5.3 shows a silicon "island" nucleation layer grown on a GaP substrate. The GaP substrate was coated with e-beam-evaporated SiO_2, and vias were photolithographically defined. Figure 5.4 shows the EDAX image, tuned for silicon, which verifies silicon growth in the vias.

These results have demonstrated the ability of selective epitaxy to grow silicon nucleation layers and point contacts on wide-bandgap, infrared-transparent GaP substrates. In addition to an oxide-passivated back surface thin-film solar cell, the inclusion of the GaP substrate obviates the need for a high-low junction back contact, and therefore permits the use of a higher base dopant concentration, which will reduce base recombination and increase open-circuit voltage.

Selective epitaxy was also used to grow a thin-film of GaP on silicon, with the objective of developing a low-recombination, transparent contact to the top (or emitter) surface. Figure 5.5 shows an EDAX line scan across the surface of a GaP film grown on a (111)-oriented silicon substrate. The interface is the edge of the grown film. Figure 5.6 shows the cleaved edge; the film is continuous, smooth, and about 1.5 microns thick. For surface passivation, a thickness of only 0.1 micron is adequate. These results indicate that liquid phase epitaxy can also be used to fabricate transparent top surface heterojunction contacts of GaP-Si.

6. SOLAR CELL RESULTS

Several experiments were performed to demonstrate the effect of light-trapping on solar cell performance. In the first, a thick epitaxial film was grown on an oxide-overcoated substrate. The resistivity of the substrate was approximately 0.01 ohm-cm; it was, therefore, electrically-inactive and did not contribute to the short-circuit current. Prior to film growth, approximately 1500 Angstroms of oxide was deposited on the substrate, and vias were photolithographically defined in the oxide layer. Using selective liquid phase epitaxy, a thick (about 200 micron) film was grown across the surface. A portion of the sample was then masked, and the film was etched to reduce the thickness of the un-masked section to less than 50 microns. In this way we were able to directly compare the effect of film thickness on cell performance. The sample was diffused with phosphine to form an n-p junction, and small mesa diodes were formed across the surface. Figure 6.1 shows the spectral response of two of the diodes which is effectively identical for wavelengths shorter than 600 nm. At longer wavelengths, however, the spectral response of the thin-base device is significantly enhanced over that of the solar cell with the thicker base. Overall, the light-generated current of the thin-base solar cell is more than 20 percent greater than that of the thick-base solar cell. These results demonstrate the current-enhancing effect of a thin-base, light-trapping solar cell structure.

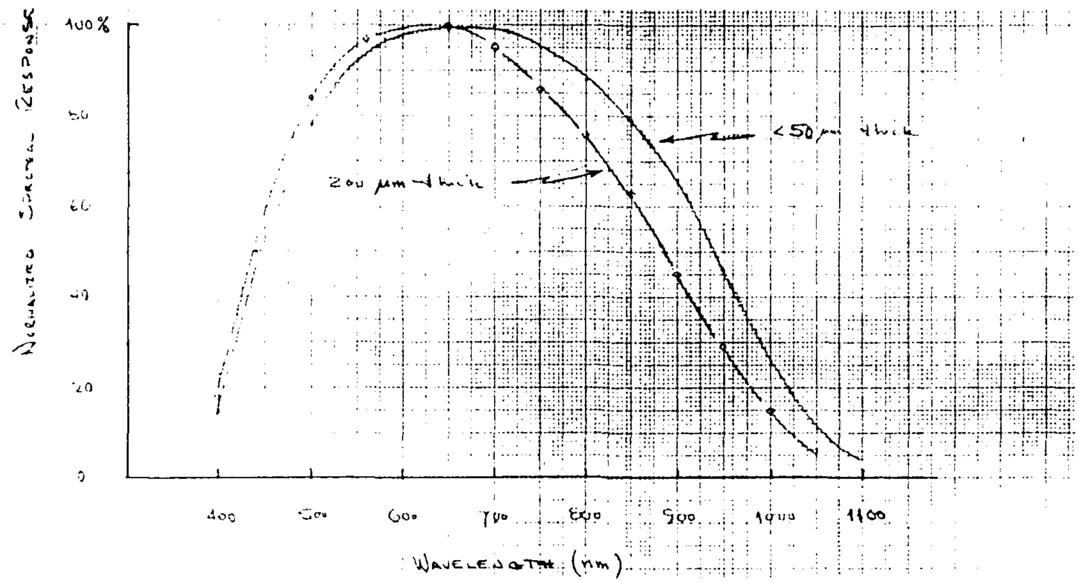

Figure 6.1 Effect of base thickness on long-wavelength response for light-trapping solar cells.

A second experiment involved growing a silicon film on an oxide-overcoated silicon substrate and comparing its performance to that of a film grown without the oxide layer. For both films, a low resistivity, electrically-inactive substrate was used. A 1500 Angstrom thick thermal oxide (SiO_2) was grown on the substrate surface, and linear vias were photolithographically defined in the oxide. After the films were grown, the samples were diffused with phosphine to form an n-p junction, a back contact (Al) was deposited, and mesa diodes (approximately 0.1 cm^2 in area) were formed across the surface. Both samples were processed at the same time to eliminate any differences due to variations in the device fabrication. For these samples, the active layer thickness was the same, about 50 microns; however, one of the samples had a full silicon-silicon back interface, and the other had oxide covering about 80 percent of the back. The results are shown in Table 6.1. Although the open-circuit voltage of the light-trapping solar cell fabricated on the oxide-coated substrate is slightly lower, the light-generated current density (Jsc) is more than 35% greater than that obtained on the uncoated substrate without a dielectric back surface reflector (BSR). These results clearly indicate the potential of a light-trapping, thin-film solar cell structure for significant current enhancement.

Table 6.1 Open-circuit voltage and short-circuit current (no antireflection coating) of thin-film silicon solar cells: oxide-overcoated (BSR) versus non-coated silicon substrates.

Film	Voc(mV)	Jsc(mA/cm^2; no AR)
A-3914 (no oxide BSR)	593	16.6
C-3915 (oxide BSR, vias)	565	22.8

A large-area film (A-3948) was grown on an oxide-overcoated substrate. As before, the substrate was electrically-inactive silicon; the oxide was thermally grown and was approximatelly 1500-Angstroms thick. Linear vias were photolithographically defined in the oxide layer. Mesa-isolated diodes were fabricated across the film. The performance of the devices was fairly uniform as determined by the open-circuit voltage. We obtained open-circuit voltages that varied less than +10 mV across an area larger than 1 cm^2. The current-voltage curve of the best solar cell (no top surface oxide passivation or anti-reflection coating) is shown in Figure 6.2. The open-circuit voltage is 583 mV, the short-circuit current density is 22.3 mA/cm2, the fill-factor is over 80%, and the equivalent AM0 efficiency (at 135 mW/cm2) is 7.7%. We estimate that the AM0 efficiency of this device with an antireflection coating, even in a non-optimized configuration, is 11.2%.

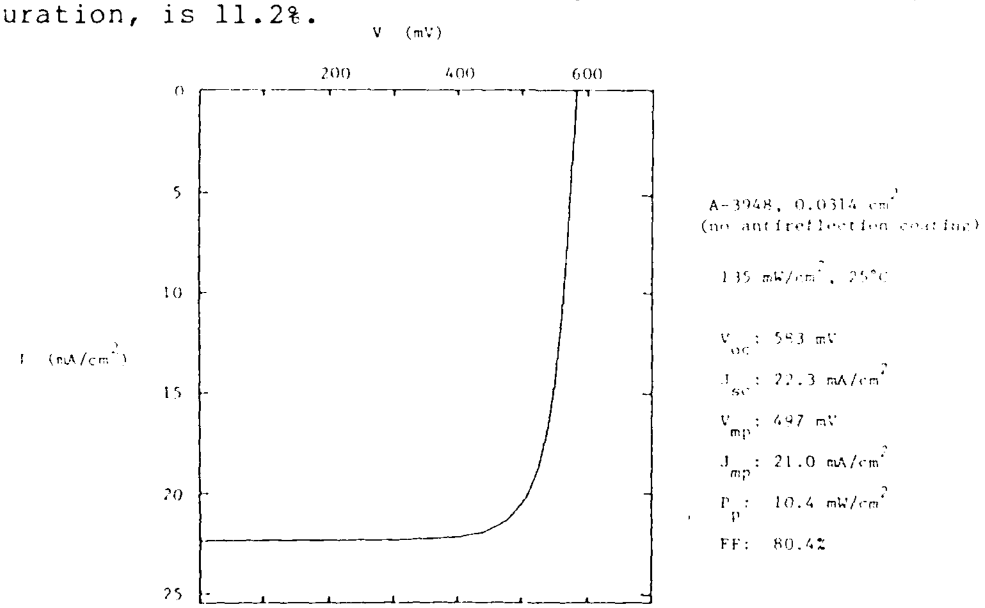

Figure 6.2 Current voltage curve of thin-film silicon-on-oxide solar cell (AM0, 135 mW/cm^2, 25°C; no antireflection coating).

The spectral response of this device is shown in Figure 6.3. Loss analysis of this device suggests that improvements in the diffused junction and passivation of the front surface should easily result in a 10% improvement in light-generated current and a factor of five reduction in minority-carrier recombination. Improved light-trapping should result in an additional 20-percent improvement in current and further reduce minority-carrier recombination. This will result in a device with an AM0 efficiency near 16% in the relatively near term. In its present state of development, heterojunction contacts would not impact the performance of this device; however, these will become important as the base and emitter recombination decrease.

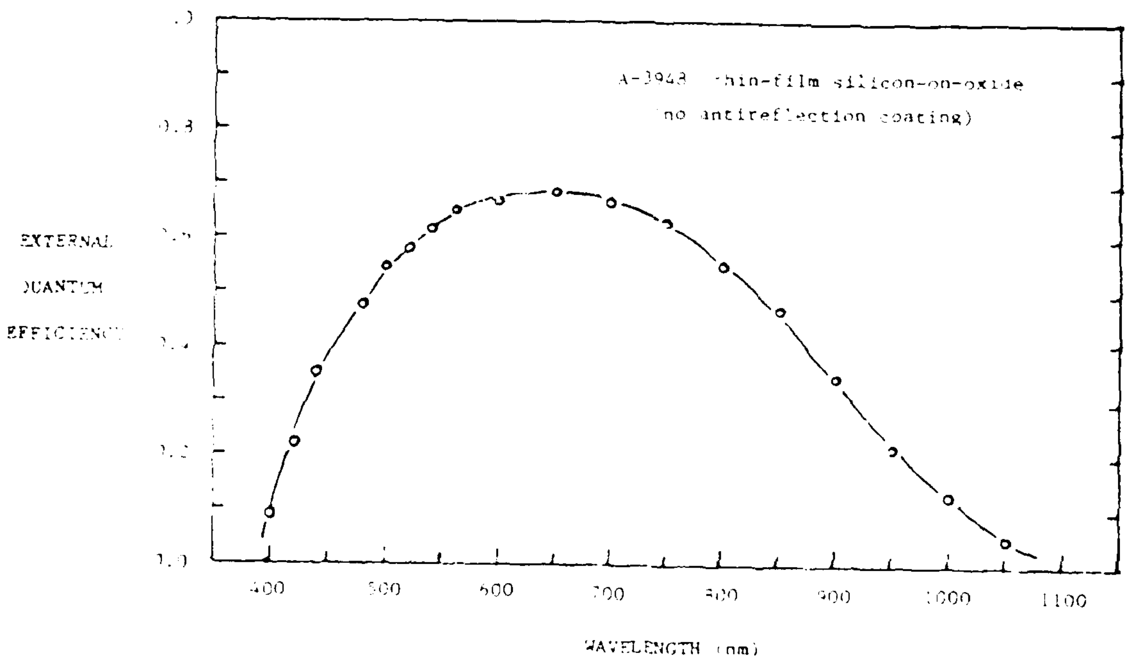

Figure 6.3 Spectral response of thin-film silicon-on-oxide solar cell; no antireflection coating.

7. FUTURE WORK

Efforts in the near term will be primarily aimed at optimizing the thin-film silicon-on-oxide solar cell. The thickness of both the grown silicon layer and the interfacial oxide layer must be varied interactively to maximize the absorptance of useful photons (with energy greater than 1.12eV). Improvements in the junction, front surface passivation, and reduced-area contacts, together with improved light-trapping, will result in near-term AM0 efficiencies of over 16%. Development of the selective epitaxial growth process will reduce base recombination so that recombination in the emitter will dominate the performance of the device. It will then be necessary to develop a heterojunction top contact; GaP may be utilized as this transparent, low recombination heterojunction contact.

During this Phase I effort, we have demonstrated selective heteroepitaxial growth of silicon on GaP substrates. The optimized thin-film silicon-on-oxide structure can be combined with a wide-bandgap GaP substrate in order to reduce back contact recombination using a silicon-GaP heterojunction. A light-trapping thin-film silicon solar cell, fabricted on an IR-transparent, heterocontact GaP substrate may have AM0 conversion efficiencies in excess of 20% when the solar cell performance is not limited by surface and contact recombination. With the light-trapping thin-base structure, current densities of 45 mA/cm^2 and open-circuit voltages well above 700 mV (with an ultimate limit of about 800 mV if operated under high injection conditions) are achievable [11,15].

8. CONCLUSIONS

During the course of this work, we have demonstrated that (1) selective epitaxy can be used to grow continuous, thin silicon films through linear vias in oxide-overcoated silicon substrates; (2) significant light-generated current enhancement results from light-trapping with a thin-film design; and (3) the silicon-on-oxide films, even in their present non-optimized condition, are capable of AM0 efficiencies in excess of 11%.

We have also shown that selective LPE can be used for successful heteroepitaxial growth of silicon on GaP, and that thin-film GaP can be grown successfully on silicon. The significance of these results is that wide-bandgap GaP is potentially useful as both a low-recombination heterojunction contact to silicon, and as a transparent top contact or substrate.

All of these films were grown by liquid phase epitaxy, a technique able to quickly produce large area, high quality films using simple and inexpensive equipment.

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10. CONTRIBUTORS

Allen M. Barnett, General Manager of the Astropower Division of Astrosystems, Inc.

Jerry S. Culik, Manager of the Device Analysis group and principal investigator for this contract.

David H. Ford, film growth engineer, responsible for the silicon-on-silicon and silicon-on-GaP growth experiments.

Gerry H. Negley, film growth engineer, responsible for the GaP-on-silicon film.

Mimi L. Rock, technician, responsible for solar cell fabrication.

Louis C. DiNetta, engineer, responsible for SEM and EDAX analysis of the films.

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